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RELATIONSHIPS BETWEEN PREATTENTIVE INFORMATION PROCESSING AND BEHAVIOURAL TASKS

Master Thesis

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Running head: MMN and behavioural tasks

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Tähelepanueelse infotöötluse ja käitumuslike mõõdike vahelised seosed

Kokkuvõte

Eeltähelepanulist infotöötlust mõõdetakse lahkenusnegatiivsuse (MMN) abil, mis võimaldab uurida erinevaid protsesse, mis muidu oleksid mõjutatud inimese kallutatusest. Käesoleva töö eesmärk oli mõista kuidas erinevad tähelepanulised protsessid seostuvad eeltähelepanulise infotöötluse mõõdikuga. Selleks kasutati kuulmise ja nägemise MMNi, mida mõõdeti EEG abil. Selleks, et operatsionaliseerida tähelepanulisi protsesse kasutati käitumuslikke mõõdikuid: *n*-tagasi, dihhootiline kuulamine, valik reaktsiooniaeg, Eesti maatriksid, numbriliste sümbolite asendamise test, stopp-signaali ülesanne, numeraalsuse ülesanne ja töömälu edasi-tagasi ülesanne. Tulemustest võib järeldada, et kõrgem kuulmise MMNi amplituud ja lühem latents on positiivselt seotud konservatiivne vastamise kaldega, mis võib olla kognitiivsete võimete hindaja. Lisaks on kuulmise ja nägemise MMN seotud erinevate tähelepanuliste protsessidega, mis võib olla tingitud auditiivse informatsiooni varasemast töötlusest võrreldes visuaalse informatsiooni töötluse ajaga.

Märksõnad: Lahknevusnegatiivsus, tähelepanueelne infotöötlus, tähelepanu töötlus, töömälu, kognitiivne võimekus

Relationships between preattentive information processing and behavioural tasks

Abstract

Mismatch negativity (MMN) is a measure of preattentive processes which allows one to look into different processes that otherwise would be subject to bias. The goal of the current study was to understand how various attentive processes relate to preattentive processing. To do that, auditory and visual MMN was measured using EEG. To capture attentive processing behavioural measures were used: *n*-back, dichotic listening, CRT, Digit symbol substitution test, Stop-signal task, numerosity task, Estonian matrices, and working memory forward and backward task. It was found that a more negative MMN amplitude and shorter peak latency is related to a more conservative responding bias, which might refer to better cognitive capacity. As well, aMMN and vMMN are related to different processes which might be due to earlier processing of auditory and later processing of visual information.

Keywords: Mismatch negativity, preattentive processing, attentive processing, working memory, cognitive capacity

Most measuring techniques in psychology require active attention and are often subject to bias. It has been suggested that preattentive processes could provide a workaround to the problem of bias, as well as could provide information about people who are not able to actively communicate (Maekawa et al., 2012). Preattentive processing refers to when information from the surroundings is processed, but it has not reached consciousness (Treisman, 1969). The preattentive processing often underlies the initiation of attention which can guide behaviour, attention and cognition (Näätänen et al., 2001, 2007).

Mismatch negativity

One of the measuring techniques to capture preattentive processing is mismatch negativity (MMN). MMN is a brain wave that is elicited by an automatic response to change meaning it does not depend on attention, hence no behavioural task is needed (Näätänen, 1992). MMN has been successfully demonstrated with auditory (aMMN; Näätänen, 1992; Näätänen et al., 2007; Näätänen & Kreegipuu, 2012), visual (vMMN; Kremláček et al., 2016; Maekawa et al., 2012), and some studies have also proposed somatosensory stimuli (for example Akatsuka et al., 2005; He et al., 2020). MMN wave is often captured with EEG; during recordings partakers are presented with a frequently occurring **standard** stimulus and infrequently occurring **deviant** stimulus, also known as oddball. For aMMN this can be a sound through headphones that varies in length, intensity or frequency (Troche et al., 2010). For vMMN, it can be a happy face among neutral ones (Kreegipuu et al., 2013). The repetition of standard stimulus generates a representation of the standard's physical features, when this representation is violated MMN is elicited (Näätänen, 1992; Näätänen & Kreegipuu, 2012). The brain is able to automatically detect the discrepancy that appears during a deviant stimulus. The MMN is then calculated by subtracting the ERP standard wave from the deviant wave generating a negative peak that can vary among people (see Figure 1). aMMN is maximally elicited over the fronto-central areas (Näätänen, 1992), and the vMMN is noted at parieto-occipital areas (Maekawa et al., 2013). MMN features used in research include peak amplitude, the most negative point usually between 150-350 ms (Näätänen et al., 2007), peak latency, the time between stimulus onset and the peak, intervals and its mean amplitude as well as activity around the peak. In this study, peak amplitude and peak latency are looked at. A more negative (i.e., higher) peak amplitude is related to better discrimination, and shorter peak latency is related to earlier processing of the deviant stimuli. Importantly, peak amplitude has more stability than peak latency.

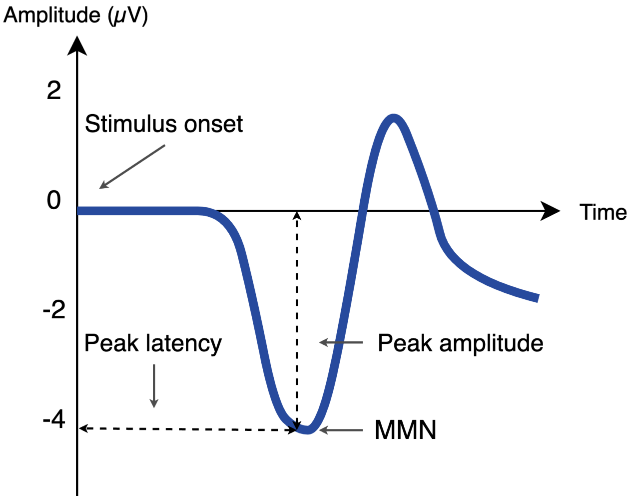

Figure 1. *MMN wave features. MMN = mismatch negativity; µV = microvolt.*

Due to its independence from the attentive processes, one of the major strengths of MMN is its objectivity. It is said that it is free from biases and hopefully, in future years it could be used as an objective predictive measure in a clinical environment (Näätänen & Kreegipuu, 2012). Yet to do that the measure should be perfected and researched, since, so far MMN has shown good replicability on a group but not an individual level.

Since MMN guides attention (Näätänen, 1992), it can be suggested that it is related to different attentive processes. The goal of the current paper is to shed more light on which attentive and cognitive processes the automatic signal is related to. After that, it would be possible to compose a 30-min long test-battery to include with aMMN and vMMN to improve the quality of future MMN research.

Mental ability and processing speed

MMN is a reflection of primitive sensory level intelligence (Näätänen et al., 2001) which suggests that mental abilities are related to MMN. Indeed, Troche and colleagues (2010) demonstrated a relationship between mental ability scores and aMMN amplitudes. In their study, 80 participants completed the full-scale Multidimensional Aptitude Battery (MAB) that measures verbal, performance and full scale IQ. EEG was then recorded while the participants were presented with the oddball paradigm. During this task they were asked to actively report when the deviant was detected. The deviant stimuli (presented 15% of the time) differentiated from the standard either with tonal frequency or duration. The authors did not find a significant relationship between any of the MAB scales and aMMN peak latency. However, higher full scale IQ was related to higher aMMN amplitude, meaning that people with higher mental abilities have better pre-attentive discrimination ability of the deviant stimuli. In another study, it was demonstrated that the aMMN response is impaired in first episode psychosis (FEP; Hermens et al., 2010). It was proposed that this decline is associated with processing speed which is essential in mental ability tasks. FEP patients and a healthy control group completed a test battery to measure neuropsychological functioning. It was demonstrated that FEP MMN peak amplitude was smaller in fronto-central and temporal areas compared to healthy controls. This difference was associated with performance on tasks that measure processing speed and attentional switching. The authors concluded that deficits in processing speed, attentional switching, simple attention, and verbal learning/memory is associated with smaller MMN peak amplitude in midline fronto-central and temporal areas.

On the other hand, in scarce studies it has been demonstrated that there is no effect of IQ on MMN amplitude. In one study, when comparing schizophrenia patients to healthy controls, IQ did not play a role in MMN amplitude variance, however, the effect could be masked by other abilities that are impaired in schizophrenia patients such as poorer cognitive capacity or working memory (WM; Javitt, 1995).

Neither study demonstrated a relationship between peak latency and intelligence. Similarly, Sculthorpe, Stelmack and Campbell (2009) found that higher MMN peak amplitude is related to higher mental ability. However, they demonstrated a link between shorter P300 (attentive) peak latency but not MMN peak latency and higher mental ability. This suggests that peak latency is associated with attending to the stimuli at later stages. Yet, within frequent gamers, who demonstrate enhanced processing speed in comparison to infrequent gamers, a trend towards a shorter aMMN peak latency has been shown (Shin et al., 2017). This suggests that quicker processing speed is related to faster preattentive processing of deviant stimuli.

To shed more light on the relationship between mental abilities and MMN features, mental abilities are looked at within this study. Digit Symbol Substitution Test (DSST) and

Estonian Matrices will be used to measure participants' mental ability. Estonian matrices are similar to Raven progressive matrices (RSPM) that has shown good validity (Raven, 2000). RSPM adequately measures fluid abilities, the ability that requires the skill to perceive visual patterns, visual-spatial imagination and verbal analytical skills. The DSST is a cognitive test that requires the participant to match symbols to numbers according to a key in a limited amount of time. In a meta analysis, Jaeger (2018) brings out that the DSST is a valuable tool in determining cognitive impairment. Due to its long history DSST has been subject to a variety of testing resulting in high reliability where language, education, and culture have little to no effect on the outcome. As a subtest of the WAIS, the DSST has undergone repeated and rigorous psychometric validation such as test-retest reliability and discriminant validity in a range of patient samples; however, modest differences exist between these versions. However, it is not clear what it actually measures. It has been proposed that the DSST is a polyfactorial measure that is affected by motor speed, attention, visuoperceptual functions, and executive functions, e.g., planning and WM (Jaeger, 2018). For example, Joy and colleagues (2004) found that processing speed explains around 50% of variance on the digit symbol task while memory accounts for 5-7%. Thus, DSST could measure processing speed which is required on many mental ability measures.

Attention Span and Cognitive Control

As mentioned, it has been previously found that MMN can be elicited without attention (Kuldkepp et al., 2013; Näätänen, 1992; Sussman et al., 2003), however, it does not mean that these processes are not related. The ability to sustain or guide attention, or the ability to grasp multiple items within an area, that can be measured during a separate task, could be related to MMN. It has been demonstrated that small and big visual numerical quantities, which could be a measure of attention span, elicit different ERP neural signatures (Hyde & Spelke, 2009, 2012). In addition, Chen and colleagues (2015) demonstrated that repeated major depressive disorder (MDD) episodes impair preattentive processing which in turn makes attention orienting more troublesome. In their study, it was found that aMMN amplitude is lower for those with MDD but no effect for peak latency was found. Together these papers suggest that attention does play a role in MMN.

To measure attention span a Numerosity task and a Dichotic listening task is employed. The goal in a Numerosity task is to correctly identify a more numerous item. It gets harder with more items and smaller discrepancies between items. Oyama, Kikuchi and Ichihara (1981) refer to this ability as span of attention. During a dichotic listening task participants hear a sound from both ears and are then asked to report what sound they heard. Usually, when not guided people report the word they heard from their right ear - this phenomenon is called the right ear advantage (REA). When attention is guided towards the word from the left ear, there is a shift to left ear advantage (LEA). Ear advantage meaning that the sound or word is more often reported correctly and from that ear. People with high cognitive control are quicker at shifting to LEA, the shifting is also influenced by WM capacity (James, 2014). In one study the MMN oddball paradigm was presented to participants monaurally, one ear at a time. The aMMN amplitude was higher in the right ear when the gap detection was smaller, meaning the ability to guide attention and discriminate gap sounds from no gap sounds is associated with higher aMMN (Todd et al., 2011).

It has been demonstrated that lower aMMN amplitude is related to poor cognitive control (Kaur et al., 2011). Cognitive control was measured by a forced left dichotic listening task. It has been suggested by Westerhausen and Hugdahl (2010) that forcing REA or LEA requires two different cognitive functions. When focusing on the information coming from the right ear, already preferred stimuli, due to left hemisphere language processing, the REA is increased due to focusing attention but during force-left resolving conflict is necessary.

Impulsivity

Impulsivity is a fast, premature, thoughtless or disinhibited behaviour (Havik et al., 2012). According to this definition one might presume that there is a relationship between impulsivity and MMN, however there are contradictory research results. Lee and colleagues (2020) demonstrated this in a recent study when comparing aMMN amplitudes of children with ADHD to children with subclinical ADHD. The children with ADHD had a significantly higher hyperactivity-impulsivity and inattention score than the subclinical group. Using a 10% oddball paradigm, they found that the aMMN mean amplitude in the fronto-central areas was lower in the ADHD group compared to the subclinical group. This suggests that higher impulsivity and inattention is related to lower MMN amplitude in those areas. Yet, the authors did not differentiate between impulsivity and inattention and how it affected the aMMN scores leaving open whether the amplitude difference was due to impulsivity or inattention. Franken and colleagues (2005), on the other hand, found the opposite in healthy adults. Using a self-report measure of dysfunctional impulsivity (difficulties with inhibition), they found a positive relationship between higher impulsivity scores and MMN amplitude, and no correlation between peak latency and MMN. This would mean that people with higher impulsivity have better discrimination of preattentive auditory deviants. These studies leave it unclear, which way the relationship is and whether peak latency plays a role in individuals' impulsivity.

In this study, to measure impulsivity a stop-signal task (SST) was used. This task measures reaction time (RT) of inhibition as well as cognitive tempo as it requires WM and response inhibition, both high cognitive load abilities. Havik and colleagues (2012) could not find a direct link between self-report impulsivity and behavioural (STT) measure impulsivity. However, they were both related to cognitive tempo suggesting that cognitive tempo underlies impulsive behaviour. Hence, impulsivity can be measured indirectly with STT.

Working Memory

There is evidence to support a relationship between WM and auditory and visual MMN, however research has its limitations. Bonetti and colleagues (2018) demonstrated in their MEG study a clear link between WM capacity and MMN. To measure WM the participants completed the Spatial Span and Letter Number sequencing task from Wechsler Memory Scale subtests and for MMN an EEG measured oddball paradigm. They found a positive relationship between WM performance and vMMN in frontal areas - higher WM capacity was related to higher peak amplitude. On the other hand, Berti and Schröger (2003) used EEG to demonstrate that there is no relationship between WM load and performance on MMN. In their oddball paradigm experiment, participants either heard a standard 1000 Hz auditory stimulus 90% of the time, or deviant 950 or 1050 Hz stimulus 10% of the time. Half of the time these different frequency tones were long (400ms) and the other half short (200ms). In the low load task the participants were asked to report whether the current sound was long or short, and in the high load task whether the preceding sound was long or short. They found that WM load did not impact aMMN, suggesting that WM capacity does not impact the elicitation of MMN.

In this paper, WM capacity is measured with WM forward (WMF) and WM backward (WMB) task also known as Digit span task, and *n*-back task. WMB task is a measure of WM and WMF is a measure of attention (Kreutzer et al., 2011). *N*-back has also been widely used as a WM measure, *N*-back accuracy d' is a valid measure to discriminate WM dysfunction (Haatveit et al., 2010). Snodgrass and Corwin (1988) used c as a measure of bias, where negative scores reflect a more liberal and positive a more conservative, more likely to reject when responding, manner. Since in their study, the effect of c on WM performance disappeared when d' was accounted for, bias is looked at as an additive to d'. However, Kane and colleagues (2007) demonstrated that N-back and digit span correlated weakly, which would indicate that the performance on n-back might not be a perfect measure of WM. However, it has been repeatedly used as a high load attention distraction task with MMN, hence, it is included in this study.

Current Study

In various studies mentioned above, a relationship between MMN features, and attentive and cognitive processes has been found. Yet, there are a lot of behavioural measures that try to capture different processes but probably no one measure can perfectly capture a cognitive process fully. Hence within this study the outcomes on measures are looked at additively. That allows us to better understand which of them relates to MMN. As both aMMN and vMMN reflect preattentive processing it is expected that similar attentive and cognitive processes are related to them (Maekawa et al., 2012). Based on the research reviewed above in total six hypotheses arose.

H1: Higher intelligence is related to higher MMN peak amplitude but not peak latency

H2: Quicker processing speed is related to higher MMN peak amplitude and shorter MMN peak latency

H3: Better selective attention is related to higher peak amplitude but not peak latency.

H4: Higher cognitive control is related to higher MMN amplitude but not peak latency

H5: There is a relationship between impulsivity and MMN peak amplitude but no relationship to peak latency

H6: Higher WM capacity is related to higher MMN amplitude, but not peak latency

Methods

Participants

Opportunity sampling was used to recruit 66 participants who were naive to the purpose of the experiment (47 females; 3 left-handed), aged between 18 and 59 years (M_{age} = 28.288, *SD* = 8.678). All of the participants completed a written consent form. Participants were recruited via social media and email lists, via posters at different schools of the University of Tartu, and via word of mouth at psychology courses and science fairs. Upon completion of both parts of the experiment the participants received compensation of 20€ gift card and/or course credit for taking part in the study. No compensation was given if the participant did not schedule the second part of data collection. The study is part of a wider project “*Seosed tähelepanueelse ja tähelepanulise infotöötluse vahel*" which was approved by the Research Ethics Committee of the University of Tartu (nr 319/T-22).

Materials and Apparatus

The online test battery was presented in Estonian via the research web environment for the Institute of Psychology of the University of Tartu Kaemus (see kaemus.psych.ut.ee). At the research lab, the tasks were presented on a LCD display (19 inch; screen resolution: 1024*768), coded using MATLAB, Psychtoolbox and E-Prime software (Psychology Software Tools, Sharpsburg, USA). The background colour was grey (rgb01 0.7 0.7 0.7) and text on it black (rgb01 0.1 0.1 0.1). The participant sat on an office chair in a dimly lit room approximately 80 cm from the computer screen. A modified computer keyboard, wired computer mouse and in-ear headphones, were used. EEG electrodes were placed according to BioSemi Inc. (see www.biosemi.com/accessoires.htm). In total 70 electrodes were placed. A cap and SignaGel were used to fix 64 electrodes on the scalp and six extra electrodes on the participants face (corners of eyes and above and below left eye; for eye-movement) and ears (for reference) using electrode specific double sided tape.

Procedure and stimuli

The study consisted of two parts - online test battery, and onsite measuring at the lab (see Figure 2). Each participant came to the lab twice, for the scope of this thesis only the data from the online test battery and first lab visit was used. The participant was informed about the procedure and asked to fill in the consent form. They were informed that they have the right to end the experiment at any given moment. The participants first completed an at home online test battery using their unique participant number, which had to be completed in one sitting. This test battery included questions about the demographic background, general health and behavioural patterns, questions about smartphone usage, musicality, personality, emotional wellbeing and affect.

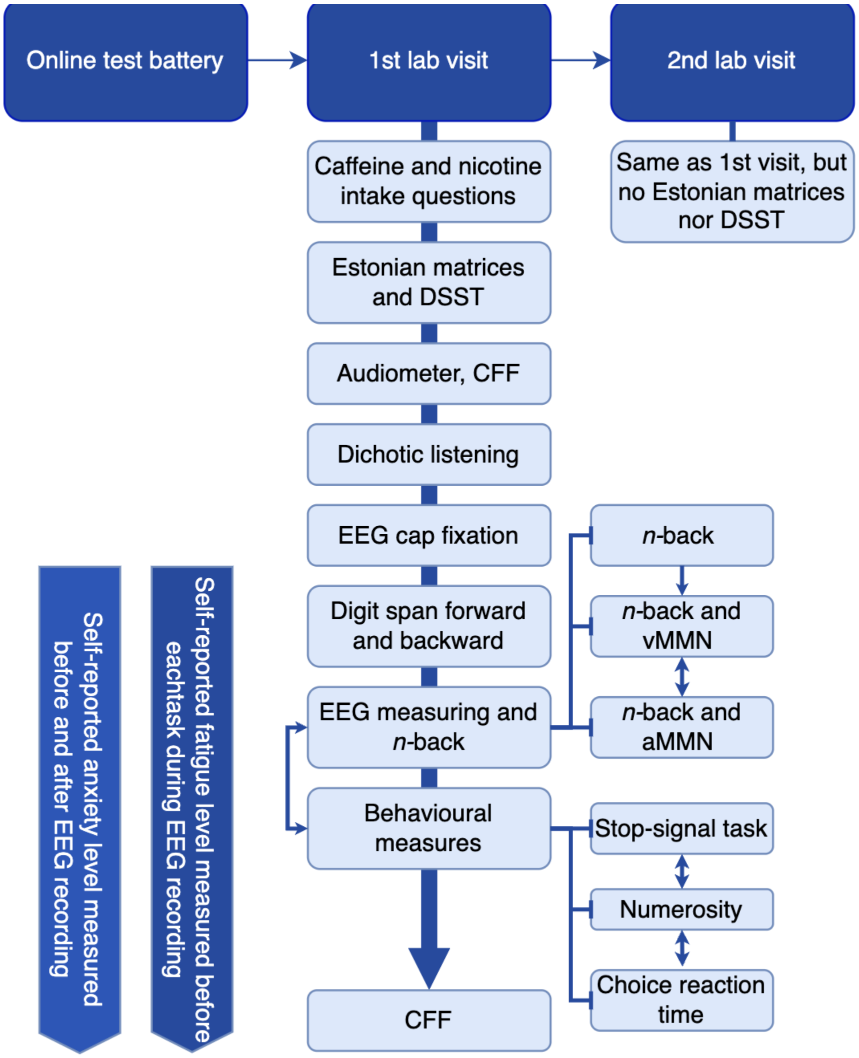

Figure 2. *Measuring structure. DSST = digit symbol substitution test; CFF = critical flicker frequency; ↔ = the order of the tasks was interchanged between participants.*

At the lab, during both visits participants answered questions about current state and sight, completed sensory measures, took part in behavioural and EEG measuring. Hearing (Audiometer, Interacoustics AS608, Assens, Denmark; 500, 1000, 1500 Hz & dB) and objective central nervous system fatigue level (CFF – critical flicker frequency, Simonson & Brožek, 1952; Hz) were first measured.

The participant was then sat on an office chair in a dimly lit room. A computer keyboard and a mouse was placed on their lap that enabled them to control the speed of the experiment. The partakers then completed the dichotic listening task. After that, within 20 to 30 minutes all EEG sensors were placed on the participants head. Before the first task, partakers reported their fatigue on a 10-point scale (0 = "not at all", 9 = "tired") and anxiety on a 6-point scale (0 = "calm", 9 = "very anxious"). These were presented throughout the measuring after each task.

When the main part of the experiment began, the participants first completed the WM measures (WMF; WMB), and then other tasks that were presented pseudorandomly but at the same order both times. They continued with either EEG measuring that started with *n*-back0 (explained below) and was followed by *n*-backA and then *n*-backV or vice versa; or other behavioural measures which appeared in a random order. All instructions were presented at the bottom of the screen in a text format. This part of the experiment lasted at least 90 minutes but the exact time depended on the participant.

Digit Symbol Substitution Test (DSST)

DSST was presented to participants on a computer screen during the first lap visit and accessed via a link, https://www.testmybrain.org/tests/DigSymbCoding/DSC.html.

Estonian Matrices (EM)

This task was presented on a computer screen and opened via a link. The goal of this task was to understand the rule within eight pictures and choose the ninth one, out of eight, that would fit the rule (see Figure 3). Thirty trials with different levels of difficulty were presented and the number of correct trials was output.

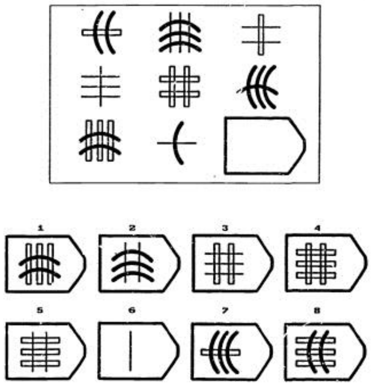

Figure 3. *Analogue to the Estonian matrices task*

WMF and WMB

During this task, the participants were presented with consonant sequences (each letter 100px). The task started with a fixation cross (500 ms) after which the first sequence was presented (each letter for 1250 ms). They were then asked to repeat the sequence back either as presented in a forward (WMF) or backward (WMB) manner. WMF was completed before the WMB task. Starting from three consonants up to twelve, hence increasing in difficulty. For each difficulty, two different sequences were presented, if the participant got at least one of them right the length was increased by one consonant if not the task ended. The number of correct trials (Blackburn & Benton, 1957) and the longest held sequence (Mathias et al., 2002) both have been used to analyse the outcome of Digit span, hence, both were used for analysis. As an outcome for each participant, the longest successful sequence and the total number of successful trials was output for both forward and backward tasks.

Numerosity

The numerosity task was inspired from Raidvee, Lember and Allik (2017). This task started with a grey circle (rgb01 0.6 0.6 0.6; 420px), after 1000 ms a collection of red (rgb01 0.89 0.302 0.204) and blue (rgb01 0.227 0.545 0.678) dots appeared for 200 ms (see Figure 4). The participants then had 3000 ms to report with a key press of which of the colours were more represented inside the grey circle – red (left arrow key) or blue (right arrow key). In total there were 9 dots in the circle. The quantity of reds and blues varied from 2:7 to 7:2 - for example, 6 red and 3 blue dots. The size (22-32px) and the distance (min 22px) between the dots also varied.

These different collections were presented randomly - each stimulus condition was presented 60 times. This part of the battery consisted of 420 trials. To begin with, participants had five trial runs. The standard deviation of the psychometric curve on the performance of the numerosity task, discrimination ability, should reflect attention span. Higher discrimination ability suggests a higher attention span (Raidvee et al., 2011).

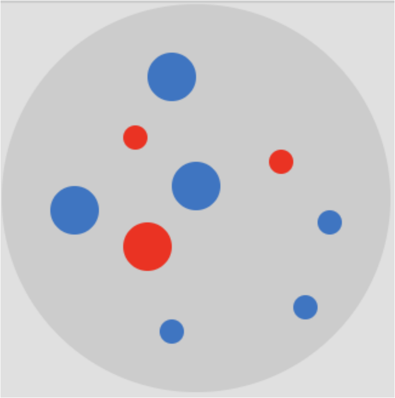

Figure 4. *Example of the numerosity task.*

Choice Reaction Time (CRT)

In the CRT task, the participant was presented with four white rectangles (80*60px) on a grey background (rgb01 0.7 0.7 0.7) in which a number (rgb01 0.1 0. 1 0.1) from one to four was presented (see Figure 5). They were asked to respond as quickly as possible when a red cross (line width 2px; rgb01 0.1 0 0; between 1000 and 3000 ms randomly) appeared across one of the four boxes by pressing 1, 2, 3, or 4 on the numbers row of the keyboard, respectively. This part of the experiment began with 8 practice trials which was then followed by 100 trials. For each participant, a mean RT across all conditions was calculated.

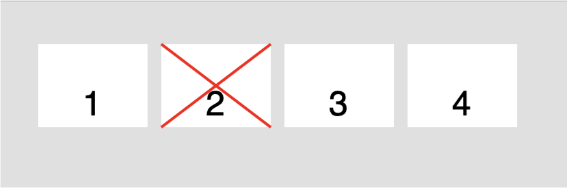

Figure 5. *Example of CRT.*

Stop-Signal Task (SST)

The STT was similar to the one used by Havik and colleagues (2012). In this task, participants saw a fixation cross (30px; rgb01 0 0 0) in the middle of the screen for 350-1000 ms; after what a full blue circle (rgb01 0 0 0.1) appeared in the middle of the screen for 1000 ms. Randomly, 25 % of the time a red cross (RGB 100) was presented on top of the blue circle with a delay beginning at 150ms. To make the task progressively easier or harder the next cross was delayed either 10ms earlier or later, respectively. When no cross appeared the delay was increased by one. During this task, the participants were asked to react by pressing a button on a keyboard as quickly and as accurately as possible when a blue circle appeared (Go-task) but to inhibit the response when the red cross appeared (NoGo-task; see Figure 6). The stimulus stayed on the screen for 1000ms after which a fixation cross appeared again. The participants had 10 practice rounds which was followed by 360 trials. For each individual, mean Go-task RT (GoRT), not inhibited NoGo-task RT i.e., Stop RT and response inhibition time was computed. Response inhibition time was calculated by subtracting the last delay time from Go-task RT.

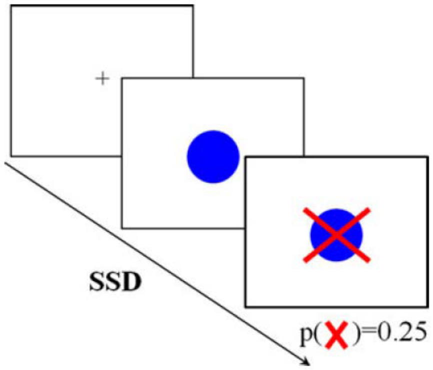

Figure 6 . *Example of STT NoGo trial; SSD = stop-signal delay.*

Dichotic Listening

This part consisted of three parts lasting three to four minute parts: free response non-forced (NF), force right (FR) and force left (FL) condition 36 stimulus pairs each. During this task, partakers heard sounds from headphones - Ba, Da, Ga, Pa, Ta, Ka. The sound from the left and right ear were different. During the free response condition the participants had to press the key corresponding to the sound heard on the modified keyboard as quickly and as accurately as possible but focus more on the accuracy. Their task was to report the sound that was more

prominent. The second part was either FR or FL depending on the participant number and the third the remaining one. During the FR condition they had to focus their attention to their right ear and report the sound; FL focus and report from the left ear. For each condition, laterality index (LI) was calculated, according to the following equation where RE is reported answers from right ear and LE reported answers from the left ear (Westerhausen & Hugdahl, 2010):
LI = 100 * (RE – LE)/(RE + LE).

MMN and N-Back

To capture the MMN wave the participants were then presented with stimuli using the oddball paradigm – 20% of the time participants were presented with a deviant and 80% of the time with standard stimuli. During the EEG recording participants were engaged with a high load WM task called *N*-back. During MMN recording, participants were instructed to focus on the WM task and ignore the MMN stimuli.

N-back0. During this task participants were presented with a series of consonants (B D H K R S T), where their task was to report whether the letter presented was the same (match condition) or not (no-match condition) as the two times back presented letter. For example, a sequence of D S R S is a match condition and a sequence of D R S S is a no-match condition (see Sultson et al., 2019). More specifically, a fixation cross (15px; RGB 111) was presented in the middle of the screen for 500 ms after which a letter (100px) appeared for 1000 ms. Partakers had 300 ms to respond with a key-press – right arrow key (blue) for match and left arrow key (red) for no-match condition. The match condition was presented randomly 30% of the time. To begin with, participants had 30 practice trials. Accuracy and RT recording was captured in four subsequent blocks of 120 letters. During this condition only the *n*-back task was presented in the middle of the screen and nothing else at the periphery nor from headphones. For each participant, mean RT of all trials (Total RT), RT of only hit trials (Hit RT), d' sensitivity and c was calculated according to mean hit and false alarm rate (Snodgrass & Corwin, 1988). EEG was recorded but is not included within this paper.

N-backA/aMMN. This part of the experiment was similar to *n*-back0 but in addition, a sequence of sounds was presented from the headphones. Each of the sounds was 100 ms long, the first standard was 1000 Hz soundwave and deviant 1200 Hz. Again, participants had 30 practice trials before 1000 recorded trials. At the beginning of recording 10 standard (1000 Hz) sounds were presented, to create a memory trace; after which the oddball paradigm started. Mid testing, after 500 trials the deviant and standard were exchanged. Again 10 standard (1200 Hz) sounds were presented then the sounds were presented in a 20:80 oddball paradigm manner. The background sound was presented for 100ms with a 350ms break and then a new one was presented. In total a 1000 sounds were presented from the headphones – a maximum seven sounds were presented from the headphones during the time one letter was presented on the screen at fovea. During this part it was asked to ignore the sound coming from the headphones and to focus only on the *N*-back task. EEG signal was recorded. MMN was calculated for both soundwaves by subtracting the standard ERP signal from the ERP signal when the same frequency soundwave was presented as a deviant. aMMN peak amplitude and peak latency between 50 and 214 ms after stimulus onset was calculated for AF3, F3, F7, AF4, Fz, F4, F8, and FCz; these were chosen due to findings from previous research, as mentioned above. As a reference; Oz electrode was used since aMMN was not expected in that area.

N-backV/vMMN. Similarly to the *N*-backA described above, in this task an oddball paradigm was used. Instead of sounds from the headphones, blinking letters (50*75px) B and T were presented at the periphery in four corners of the screen during the *n*-back task at the fovea (see Figure 7). The letter B was first assigned as a standard and presented 10 times before 20:80 oddball; similarly to *N*-backA the standard was switched midway and T was then presented as standard. The background image was presented for 450ms with a 250ms break and then a new one was presented. In total a 1000 letters were presented in the periphery - this means that 5 letters maximum were presented in the periphery during which one letter was presented at the fovea. During this part it was asked to ignore the letter in the periphery and focus on the task at hand, nothing was presented from the headphones. vMMN peak amplitude and peak latency between 135 and 300 ms after stimulus onset, were calculated for PO7, PO3, O1, O2, POz, PO8, PO4, Oz; these were chosen due to findings from previous research, as mentioned above. As a reference; Fz electrode was used as a reference since vMMN was not expected in that area.

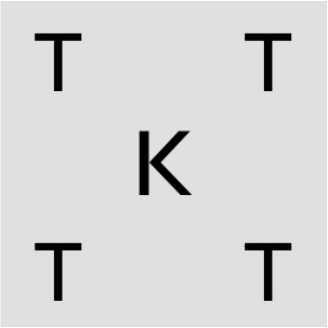

Figure 7. *Example of N-backV. The MMN task is presented at the periphery while n-back at the fovea.*

Design

A within-subjects design was used in this exploratory study. All participants were presented with all conditions. The independent variables were behavioural measures: WMF and WMB span and number of correct trials, discrimination accuracy from the numerosity task, EM score, CRT, GoRT, StopRT and response inhibition time from the SST task, LI for non-forced, forced-right and forced-left from the dichotic listening task, DSST score, Total RT, Hit RT, d’ sensitivity and c from all *n*-back conditions. The dependent variables were aMMN and vMMN peak amplitude and peak latency.

To understand the relationship between MMN amplitude and peak latency and behavioural measures principal component analysis (PCA), Shapiro-Wilk test for normality check, Pearson's correlation for normally distributed variables, Spearman's correlation for non-normally distributed data, and Multiple linear regression were used.

Results

MMN

During aMMN recording for one participant MMN amplitude or peak latency was not included due to technical difficulties. In addition, outliers were removed cell-wise when the MMN amplitude or peak latency varied 3 or more standard deviations from the mean. This resulted in the removal of seven amplitude and two peak latency recordings of aMMN and 13 vMMN amplitude cells across ten participants. Each location had no more than one removal.

One sample t-test against zero revealed that significant aMMN and vMMN was elicited in all of the areas selected, for all stimulus types, including the reference sites (see Figure 8 and 9), hence the prerequisite for looking relationships between MMN features and behavioural measures was accomplished.

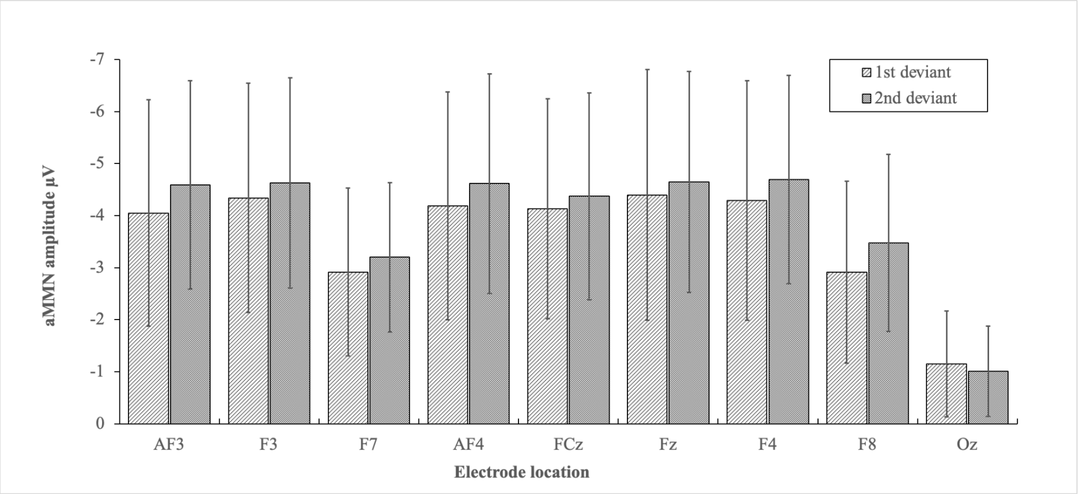

Figure 8. *aMMN amplitude at different electrode locations. A = anterior; F = frontal; C = central; O = occipital; odd number = left side; even number = right side; z = central line. Error bars represent ± 1 standard deviation.*

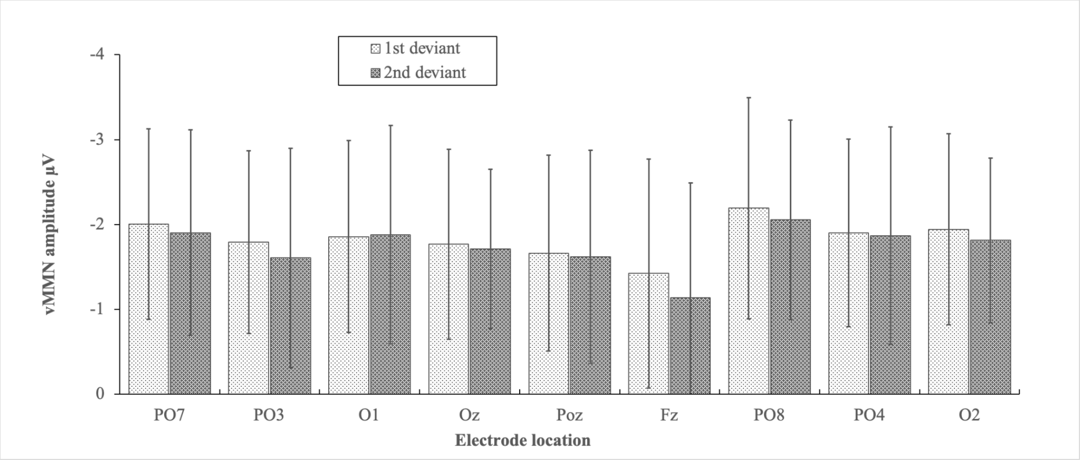

Figure 9. *vMMN amplitude at different electrode locations. P = posterior; F = frontal; O = occipital; odd number = left side; even number = right side; z = central line. Error bars represent ± 1 standard deviation.*

A correlation between 18 aMMN electrode recordings and 18 vMMN recordings revealed only eight 2.79% significant correlations between aMMN and vMMN correlation varying from .249 to .399. Whereas 77.6% of aMMN electrode recordings were significant and 39.47% of vMMN electrode recordings were significant. Thus, it is reasonable to look at vMMN and aMMN separately.

To reduce dimensionality to two components, a principal component analysis (PCA) with oblimin promax rotation on aMMN amplitude values was applied. Correlation matrix between components revealed low correlation between components (<.32; Brown, 2009) which called for orthogonal varimax rotation. The same logic was used in further PCAs as well. Thus, orthogonal varimax rotation with Eigenvalues greater than 1.00 yielded a component structure given in Table 1. Two principal components accounted for 69.6% of the variance in total. For further analysis, variables with a loading higher than .5 were included. This resulted in a first component consisting of aMMN amplitudes that were elicited by the **second** deviant (1200Hz) at Fz, AF4, FCz, AF3, F4, F3, F8, and F7, hence it would be reasonable to call it “aMMN 2nd amplitude”. The second component consisted of aMMN amplitudes that were elicited by the **first** deviant (1000Hz) at F7, F3, FCz, AF3, Fz, AF4, F4, and F8, named “aMMN 1st amplitude”. The aMMN 2nd amplitude component accounted for 55% and aMMN 1st amplitude component for 14.6%. A Cronbach's α analysis revealed a good internal consistency for both first, α = 0.956, and second, α = 0.953, components. The variables in the components were used to generate new values for each participant by averaging the amplitude of each electrode location within a component, hence resulting in two new variables: “aMMN 2nd amplitude” and “aMMN 1st amplitude”.

PCA orthogonal varimax rotation for aMMN peak latency values was used. This resulted in a component structure given in Table 2. The first two principal components accounted for 55.5% of the variance in total. Again, for further analysis, variables with a loading higher than .5 were included. This resulted in a first component consisting of aMMN peak latency estimates that were elicited by the **first** deviant (1000Hz) at Fz, AF4, FCz, AF3, F4, and F3, hence it would be reasonable to call it “aMMN 1st peak latency”. The second component consisted of aMMN peak latency estimates that were elicited by the **second** deviant (1200Hz) at F3, FCz, AF3, Fz, AF4, and F4, named “aMMN 2nd peak latency”. The aMMN 1st peak latency component accounted for 32.8% and aMMN 2nd peak latency component for 22.2%. A

Cronbach's α analysis revealed a good internal consistency for both first, α = 0.932, and second, α = 0.906, components. Similarly to aMMN amplitude two new variables were generated for aMMN peak latency: aMMN 1st peak latency and aMMN 2nd peak latency.

PCA orthogonal varimax rotation for vMMN amplitude values was used. This resulted in a component structure given in Table 3. The first two principal components accounted for 57.2% of the variance in total. Again, variables with a loading higher than .5 were chosen, however, Oz 1st deviant amplitude variable was excluded from the second component since it loaded to the third component more. This resulted in a first component consisting of vMMN amplitude variables that were elicited by the **second** deviant ("B") at Oz, PO3, POz, PO4, O2, O1, PO8, and PO7, hence it would be reasonable to call it "vMMN 2nd amplitude". The second component consisted of vMMN amplitudes that were elicited by the **first** deviant ("T") at POz, PO4, PO8, and O2, named "vMMN 1st amplitude". The vMMN 2nd amplitude component accounted for 30.5% and vMMN 1st amplitude component for 26.7%. A Cronbach's α analysis revealed a good internal consistency for both first, α = 0.912, and second, α = 0.836, components. Similarly to aMMN amplitude two new variables were generated for vMMN amplitude: vMMN 2nd amplitude and vMMN 1st amplitude.

PCA orthogonal varimax rotation for vMMN peak latency values was used. This resulted in a component structure given in Table 4. The first two principal components accounted for 40.8% of the variance in total. Again, for further analysis, variables with a loading higher than .5 were included, however, Oz 1st deviant amplitude variable was excluded from the first component since it loaded to the third more and it is not clear to which of the two it best describes. This resulted in a first component consisting of vMMN peak latency estimates that were elicited by the **first** deviant ("T") at POz, O1, PO3, and PO4, hence it would be reasonable to call it "vMMN 1st peak latency". The second component consisted of vMMN peak latency estimates that were elicited by the **second** deviant ("B") at PO3, PO7, O1, POz, and Oz, named "vMMN 2nd peak latency". The vMMN 1st peak latency component accounted for 24.4% and vMMN 2nd peak latency component for 16.4%. A Cronbach's α analysis revealed a good internal consistency for both first, α = 0.829, and second, α = 0.765, components. Similarly to aMMN amplitude two new variables were generated for vMMN peak latency: vMMN 1st peak latency and vMMN 2nd peak latency.

Table 1. Component Loadings aMMN amplitude

MMN electrode	**PC1**	**PC2**	**PC3**	**Uniqueness**
Fz aMMN 2nd amplitude	**0.900**	0.314	0.027	0.091
AF4 aMMN 2nd amplitude	**0.885**	0.317	-0.116	0.103
FCz aMMN 2nd amplitude	**0.882**	0.255	0.121	0.142
AF3 aMMN 2nd amplitude	**0.868**	0.404	-0.033	0.082
F4 aMMN 2nd amplitude	**0.865**	0.333	-0.052	0.139
F3 aMMN 2nd amplitude	**0.853**	0.314	-0.003	0.175
F8 aMMN 2nd amplitude	**0.747**	0.239	-0.251	0.323
F7 aMMN 2nd amplitude	**0.662**	0.013	-0.019	0.562
F7 aMMN 1st amplitude	0.370	**0.548**	-0.186	0.528
F3 aMMN 1st amplitude	0.318	**0.850**	0.009	0.176
FCz aMMN 1st amplitude	0.301	**0.861**	0.044	0.166
AF3 aMMN 1st amplitude	0.271	**0.886**	-0.197	0.102
Fz aMMN 1st amplitude	0.265	**0.911**	0.025	0.100
AF4 aMMN 1st amplitude	0.229	**0.864**	-0.133	0.183
F4 aMMN 1st amplitude	0.213	**0.924**	-0.008	0.102
F8 aMMN 1st amplitude	0.155	**0.689**	-0.412	0.332
Oz aMMN 2nd amplitude	-0.050	-0.199	0.655	0.529
Oz aMMN 1st amplitude	0.006	0.043	0.870	0.240

Note. Applied rotation method is varimax. Bolded loadings (factor loading > .5) were included in further analysis

Table 2. Component Loadings aMMN peak latency

MMN electrode	PC1	PC2	PC3	PC4	PC5	Uniqueness
Fz aMMN 1st latency	**0.941**	0.071	0.160	0.016	-0.058	0.081
FCz aMMN 1st latency	**0.901**	0.080	-0.032	-0.024	0.058	0.178
AF4 aMMN 1st latency	**0.883**	0.061	0.149	0.001	0.012	0.195
F3 aMMN 1st latency	**0.872**	0.090	0.267	0.040	-0.070	0.154
AF3 aMMN 1st latency	**0.795**	0.011	0.343	0.073	-0.048	0.242
F4 aMMN 1st latency	**0.714**	0.145	-0.291	0.067	0.018	0.379
F3 aMMN 2nd latency	0.161	**0.883**	-0.002	-0.035	-0.004	0.193
Fz aMMN 2nd latency	0.044	**0.864**	0.013	-0.009	-0.203	0.210
AF4 aMMN 2nd latency	0.115	**0.837**	0.087	0.258	0.076	0.207
AF3 aMMN 2nd latency	-0.196	**0.798**	0.209	0.192	0.079	0.237
F4 aMMN 2nd latency	0.098	**0.774**	0.187	0.223	0.257	0.241
FCz aMMN 2nd latency	0.156	**0.768**	-0.044	-0.169	-0.014	0.355
F8 aMMN 1st latency	0.150	0.183	0.813	0.037	0.073	0.276
F7 aMMN 1st latency	0.398	-0.035	0.539	-0.232	-0.353	0.372
F7 aMMN 2nd latency	0.230	0.445	0.419	0.293	0.002	0.488
F8 aMMN 2nd latency	-0.060	0.450	0.295	0.580	0.308	0.276
Oz aMMN 2nd latency	-0.089	-0.038	0.084	-0.854	0.131	0.238
Oz aMMN 1st latency	-0.000	0.020	-0.011	-0.068	0.893	0.198

Note. Applied rotation method is varimax. Bolded loadings (factor loading > .5) were included in further analysis.

Table 3. Component Loadings vMMN amplitude

MMN electrode	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**Uniqueness**
Oz vMMN 2nd amplitude	**0.898**	0.064	-0.044	-0.022	0.071	0.182
PO3 vMMN 2nd amplitude	**0.878**	-0.030	0.160	-0.075	0.189	0.161
POz vMMN 2nd amplitude	**0.849**	-0.192	0.047	-0.173	-0.084	0.204
PO4 vMMN 2nd amplitude	**0.844**	0.040	-0.196	-0.085	0.012	0.241
O2 vMMN 2nd amplitude	**0.797**	0.122	-0.050	0.247	-0.236	0.231
O1 vMMN 2nd amplitude	**0.740**	0.042	0.233	0.304	0.175	0.273
PO8 vMMN 2nd amplitude	**0.672**	0.172	-0.207	0.372	-0.335	0.225
PO7 vMMN 2nd amplitude	**0.659**	-0.071	0.283	0.374	0.247	0.280
PO8 vMMN 1st amplitude	0.022	**0.821**	0.174	-0.043	-0.108	0.282
PO4 vMMN 1st amplitude	-0.074	**0.784**	0.268	0.091	0.153	0.277
O2 vMMN 1st amplitude	-0.010	**0.712**	0.549	0.072	0.002	0.187
POz vMMN 1st amplitude	0.108	**0.711**	0.253	-0.218	0.313	0.273
Oz vMMN 1st amplitude	0.039	0.538	0.696	-0.040	-0.021	0.223
PO7 vMMN 1st amplitude	-0.072	0.193	0.858	0.227	-0.096	0.160
O1 vMMN 1st amplitude	0.087	0.403	0.783	-0.201	0.070	0.171
PO3 vMMN 1st amplitude	0.067	0.350	0.669	-0.053	0.366	0.288
Fz vMMN 2nd amplitude	0.086	-0.083	0.009	0.854	0.177	0.225
Fz vMMN 1st amplitude	0.046	0.139	0.013	0.214	0.838	0.230

Note. Applied rotation method is varimax. Bolded loadings (factor loading > .5) were included in further analysis. Oz 1st deviant not included.

Table 4. Component vMMN latency

MMN electrode	PC1	PC2	PC3	PC4	PC5	PC6	Uniqueness
POz vMMN 1st latency	**0.806**	-0.154	0.119	0.024	-0.182	-0.061	0.275
O1 vMMN 1st latency	**0.796**	0.124	0.125	0.017	-0.093	-0.149	0.305
PO3 vMMN 1st latency	**0.790**	0.022	0.059	-0.044	0.098	-0.022	0.360
PO4 vMMN 1st latency	**0.750**	0.055	0.233	0.110	0.185	0.117	0.320
Oz vMMN 1st latency	0.553	0.042	0.557	-0.004	-0.109	-0.127	0.355
PO3 vMMN 2nd latency	0.162	**0.782**	0.041	0.062	-0.055	0.090	0.346
PO7 vMMN 2nd latency	-0.003	**0.776**	-0.080	-0.050	0.312	-0.075	0.286
O1 vMMN 2nd latency	-0.205	**0.704**	0.238	0.144	-0.254	-0.015	0.320
POz vMMN 2nd latency	0.112	**0.616**	0.124	0.335	-0.300	0.215	0.344
Oz vMMN 2nd latency	-0.031	**0.519**	0.178	0.448	0.247	-0.406	0.271
O2 vMMN 1st latency	0.269	0.053	0.863	0.017	-0.005	0.130	0.163
PO8 vMMN 1st latency	0.137	0.111	0.838	-0.054	-0.158	0.003	0.239
O2 vMMN 2nd latency	-0.005	0.137	0.107	0.880	0.164	0.010	0.169
PO4 vMMN 2nd latency	0.194	0.333	-0.008	0.556	-0.193	0.521	0.234
Fz vMMN 1st latency	-0.045	-0.101	-0.240	-0.062	0.745	0.157	0.347
Fz vMMN 2nd latency	-0.219	0.026	0.076	-0.049	0.174	0.799	0.275
PO8 vMMN 2nd latency	0.006	0.017	-0.159	0.622	-0.201	-0.060	0.544
PO7 vMMN 1st latency	0.481	0.187	0.408	0.006	0.483	-0.195	0.296

Note. Applied rotation method is varimax. Bolded loadings (factor loading > .5) were included in further analysis. Oz 1st deviant not included.

Behavioural measures

Outcomes on SST for two participants were excluded pairwise due to not engaging in the task (less than 2 responses on the GoTrial). Responses on the *n*-back task were excluded when hit rate was below chance (66%) and response rate below 75%. Due to this criteria, 16 response cells were excluded in *n*-back0 task, five on *n*-backA task and nine on *n*-backV task. The audiometer revealed that one participant had an ear difference of 15dB, and hearing threshold in the left ear was over 20db due to which one participant's response for all three conditions from the dichotic listening task were excluded from analysis (Todd et al., 2011). Similarly, to MMN measures responses were removed if varied more than 3 standard deviations from the mean.

A Spearman's and Pearson's analysis revealed a high correlation between hit rate RT and total RT in *n*-back0, r = .920; p <.001, *n*-backA, r = .915; p <.001, and *n*-backV, r = .891; p <.001, task. Since, accuracy on *n*-back task is captured with d' and c *n*-back hit rate RT was excluded from further analysis. Further, due to the high correlation, r = .88; p <.001, between RT on *n*-backV and *n*-backA tasks these were averaged generating a new variable, *n*-back MMN RT, for each participant. In addition, a high correlation between the two measures of digit span tasks - number of correct trials and longest held sequence, forward rho = .898; p <.001; backward rho = .921; p <.001, the longest held sequence was kept for further analysis. Lastly, on SSD Go trial RT and Stop RT correlated highly, r = .942; p <.001. Since it has been previously suggested that Stop RT could be a measure or functional impulsivity (Havik et al., 2012), Go trial RT was dropped and Stop RT kept in further analysis.

Hence, 66 DSST, WMB and WMF; 65 EM; 64 response inhibition, stop RT, LI-NF, and LI-FL; 63 numerosity, 63 nback0 RT, *n*-back MMN RT, CRT, and LI-FR; 61 nbackA d' and c; 57 nbackV c; 55 nbackV d'; 50 nback0 d' and 49 nback0 c responses were included in further analysis. The responses were then standardised using Excel "Standardize" function to reduce the bias for higher values is further PCA. The descriptive outcomes on the behavioural tasks are presented in Table 5.

Table 5. Descriptive data of the behavioural measures

	Mean	**SD**
DSST	50.500	9.242
Estonian matrices	25.492	2.884
Numerosity	0.103	0.050
WMF	5.800	1.277
WMB	5.569	1.346
Stop RT	436.418	93.172
Response inhibition time	198.504	75.574
CRT	509.100	108.983
LI-NF	3.613	21.768
LI-FR	12.629	17.250
LI-FL	0.682	20.794
***n*-back0 RT**	827.719	191.128
***n*-backMMN RT**	719.840	137.763
***n*-back0 d'**	2.005	0.796
***n*-backA d'**	2.231	0.963
***n*-backV d'**	2.127	0.796
***n*-back0 c**	0.335	0.279
***n*-backA c**	0.439	0.316
***n*-backV c**	0.386	0.325

Note. d’ = sensitivity; c = choice criterion; DSST = Digit symbol substitution test; CRT = choice reaction time; WMB = WM backwards span; WMF = WM forwards span; StRT = stop reaction time; LI = laterality index; FR = forced-right; NF = non-forced; RT = reaction time.

MMN and behavioural measures

To check for a relationship between MMN components and behavioural measures, a Spearman's and Pearson's correlation with pairwise complete cases was run. The analysis revealed eight significant correlations (see Table 6). A significant correlation between aMMN 2nd amplitude and nbackA c, r = -.329; p = .010; between aMMN 1st amplitude and nback0 c, r = -.393; p = .006; between aMMN 1st peak latency and EM r = -.301; p = .016; between aMMN 2nd peak latency and n-back0 RT rho = -.348; p = .006, and WMF rho = -.272; p = .030; between vMMN 2nd amplitude and *n*-back0 d' rho = -.290; p = .041; between vMMN 1st amplitude and LI-NF r = .259; p = .039; and between vMMN 2nd peak latency and nback0 c rho = .433; p = .002. This result suggests that increased (more negative) MMN amplitude is related to more conservative responding bias, better WM span, a more right sided laterality; shorter MMN peak latency is related to higher fluid intelligence, longer RT, a more liberal responding bias and better WM capacity.

To understand whether multiple independent variables measure one underlying process, a PCA with orthogonal varimax rotation, components based on Eigenvalues over 1, was applied on behavioural measures. Since data exclusion was not the goal of the analysis all of the components were included in the following analysis. For each component, variables with a loading higher than .5 were chosen. This resulted in six components in total that accounted for 70.5% of variance in the data (see Table 6):

1. PC1 - "Intelligence" component that consisted of the sensitivity d' on *n*-back tasks, EM score and discrimination accuracy of the numerosity task. This component accounted for 24% of variance.
2. PC2 - "Processing speed" component consisted of CRT, DSST, and RT on the *n*-back task. This component accounted for 14.8% of variance.
3. PC3 - "Responding bias" component consisted of the choice criterion c on the *n*-back tasks, accounting for 9.5% of variance.
4. PC4 - "Selective attention" component consisting of the LI of NF and FR condition on the dichotic listening task. This component accounted for 9.2% of variance.
5. PC5 - "Impulsivity" consisting of the LI of forced left condition on the dichotic listening task, SST, and response inhibition, accounting for 6.7% of variance.
6. PC6 - "RDS (real digit span)" consisting of WMF and WMB digit span, accounting for 6.3% of variance.

Table 6. Component Loadings of behavioural measure parameters

Variables	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**	**Uniqueness**
nback0 d’	**0.751**	-0.214	-0.264	-0.055	-0.188	-0.170	0.254
nbackV d’	**0.732**	-0.201	-0.371	0.073	0.071	0.125	0.260
Discrimination accuracy	**-0.710**	-0.396	0.113	-0.027	0.020	-0.065	0.321
EM	**0.695**	-0.010	0.003	-0.097	0.099	0.308	0.403
nbackA d’	**0.684**	-0.231	-0.289	0.302	-0.147	0.064	0.278
nbackMMN RT	-0.016	**0.857**	0.090	0.030	-0.204	-0.067	0.210
nback0 RT	0.046	**0.772**	0.114	-0.119	-0.152	-0.065	0.347
CRT	-0.363	**0.709**	-0.195	-0.126	0.223	0.066	0.258
DSST	0.483	**-0.565**	0.082	-0.191	-0.173	0.302	0.283
nbackV1 c	-0.340	0.074	**0.810**	0.059	0.105	0.018	0.207
nbakcA c	-0.109	-0.086	**0.775**	-0.194	-0.018	-0.007	0.342
nback0 c	-0.125	0.113	**0.634**	0.250	0.339	-0.035	0.392
LI-FR	0.071	-0.112	0.021	**0.873**	-0.153	-0.028	0.196
LI-NF	-0.042	0.008	-0.030	**0.784**	0.176	0.010	0.351
StRT	0.258	0.364	-0.116	0.251	**-0.729**	0.249	0.131
LI-FL	0.232	0.102	0.051	0.272	**0.632**	0.122	0.445
Response inhibition	-0.237	-0.267	0.364	-0.100	**0.541**	-0.038	0.436
WMB	0.266	-0.112	0.255	-0.057	-0.115	**0.759**	0.259
WMF	0.002	-0.037	-0.221	0.047	0.053	**0.841**	0.237

Note. Applied rotation method is varimax. Values standardised.

Discrimination accuracy, DSST score and StRT were reverse scaled by adding together the minimum and maximum value and subtracting the score for each. A Cronbach's α analysis revealed a high internal consistency for the first, α = .826, second, α = .769, third, α = .737, and fourth, α = .709 component and a moderate internal consistency for fifth, α = .554, and sixth, α =

.538, component. Similarly to MMN components, values on each item in a component were averaged for each participant generating six new variables. Higher values on the:

1. intelligence variable means higher mental abilities,
2. processing speed variable means slower processing speed,
3. responding bias variable suggests a more conservative responding style,
4. selective attention variable indicates a better ability to orient attention,
5. impulsivity variable indicates more impulsive behaviour.
6. RDS variable indicates better WM capacity

Table 7. Correlation between behavioural measures and components, and MMN variables

MMN parameter	**Behavioural measures**	**Correlation**	**p**
aMMN 2nd amplitude	*n*-backA c	-0.329*	0.010
aMMN 1st amplitude	*n*-back0 c	-0.393**	0.006
aMMN 1st latency	EM	-0.301*	0.016
aMMN 2nd latency	*n*-back0 RT	-0.348*	0.006
aMMN 2nd latency	WMF	-0.272*	0.030
vMMN 2nd amplitude	*n*-back0 d'	-0.290*	0.041
vMMN 1st amplitude	LI-NF	0.251*	0.045
vMMN 2nd latency	*n*-back0 c	0.433**	0.002
	PCA components		
aMMN 2nd amplitude	Responding bias	-0.296*	0.021
aMMN 1st amplitude	Responding bias	-0.279*	0.029
aMMN 2nd latency	RDS	-0.271*	0.029
vMMN 2nd latency	Impulsivity	0.283*	0.021

Note. * p < .05, ** p < .01, *** p < .001 Italics = Spearman’s rho. RDS = real digit span; RT = reaction time; c = choice criterion; WMF = WM forward span; d’ = responding accuracy.

Again, to check for a relationship between MMN and behavioural measures, a Spearman's and Perason's analysis was applied between eight MMN and six behavioural measures components. The analysis revealed eight significant correlations (see Table 7) – between aMMN 2nd amplitude and responding bias, r = -.296; p = .021; between aMMN 1st amplitude and responding bias r = -.279; p = .029; between aMMN 2nd peak latency and RDS r = -.271; p = .029; and between vMMN peak latency and impulsivity r = .283; p = .021 (see Figure 10). In line with previous correlation on behavioural measures, these results agree that larger aMMN (more negative) absolute value amplitude is related to more conservative responding type and shorter peak latency to higher WM capacity. Additionally, delayed peak latency is related to higher impulsivity.

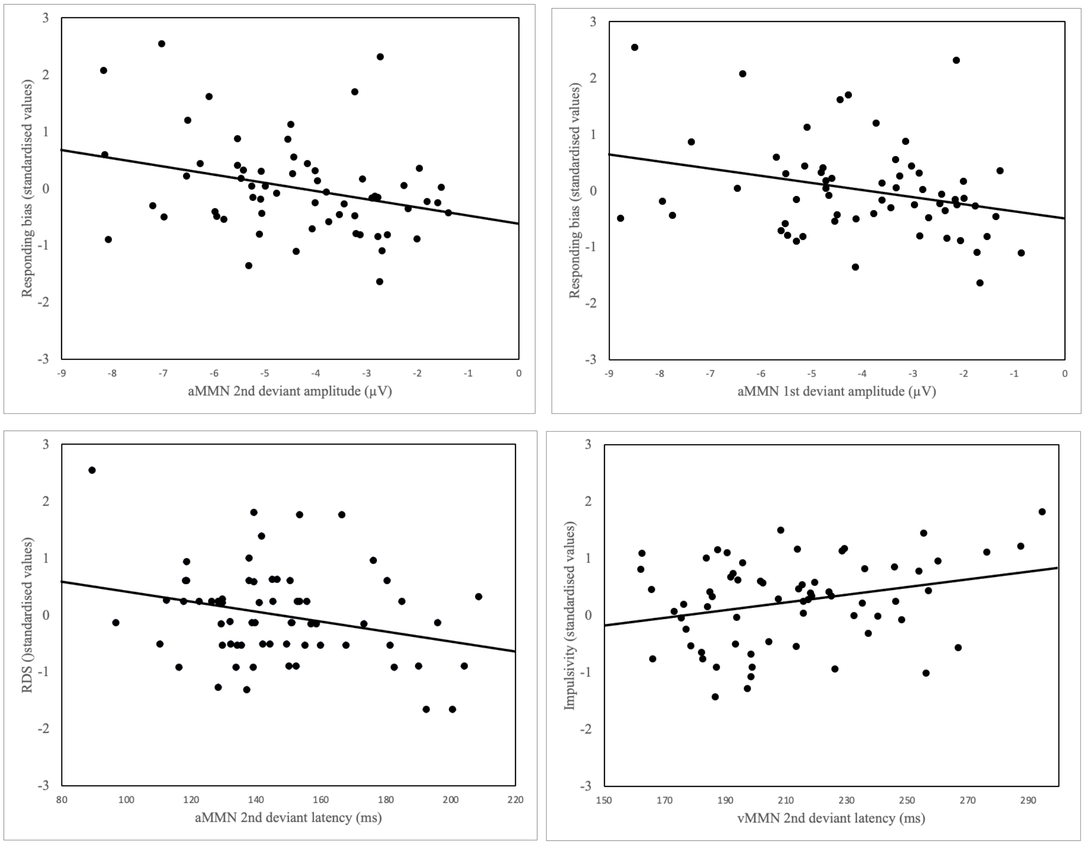

Figure 10. C*orrelations between MMN features and behavioural components.*

Multiple regression

Hierarchical backward multiple linear regression was used to check whether multiple behavioural components could additively predict amplitude and/or peak latency on MMN components. Age was added in addition to behavioural components. Multiple components models with highest adjusted R squared or one component model R squared that significantly improved the prediction of MMN amplitude or peak latency compared to mean were chosen. All chosen models' Durbin-Watson score was non-significant and between 1.5 and 2.5, hence, no first order autocorrection was suspected. All components tolerance was above .1 and VIF was below 10, meaning there is no danger of multicollinearity.

aMMN 2nd amplitude (1000Hz as deviant)

Multiple linear regression using backward data entry shows that intelligence, responding bias, attention orienting, and RDS (see Table 8) significantly explain 12.5% of the variance in Auditory 2nd deviant amplitude component F(4,54) = 3.080, p = .023, adjusted R squared = .125. Amplitude could be predicted using a regression equation of Amplitude = -4.593 + (.319 * Intelligence) + (-.248 * Responding bias) + (-.184 * Attention orienting) + (-.188 * RDS); the absolute value of amplitude decreases with intelligence, and increases with a more conservative responding bias, higher selective attention, and higher WM capacity. Residuals and predicted graph suggested a slight violation of homoscedasticity. Of note, 5.17% of residuals absolute value exceeded two, hence, the regression line might not describe the data the best.

Table 8. Multiple regression for predicting aMMN 2nd amplitude (μV)

Components	**B**	**β**	**t**	**p**
(Intercept)	-4.593		-19.470	< .001
Intelligence	0.554	0.241	1.737	0.088
Responding bias	-0.525	-0.248	-1.907	0.062
Attention orienting	-0.363	-0.184	-1.488	0.143
RDS	-0.396	-0.188	-1.439	0.156

Note. B = unstandardised coefficient; β = standardised coefficient; RDS = real digit span

aMMN 1st amplitude (1200Hz as deviant)

Multiple linear regression using backward data entry shows responding bias (see Table 9) can significantly explain 7.2% of the variance in aMMN 1st amplitude component F(1,57) = 4.411, p = .040, R squared = .072. Amplitude could be predicted using a regression equation of Amplitude = -4.010 + (-.268 * Responding bias); the absolute value of aMMN 1st amplitude increases with a more conservative responding type. Of note, 5.17% of residuals absolute value exceeded two, hence, the regression line might not describe the data the best.

Table 9. Multiple regression for predicting aMMN 1st amplitude (μV)

Components	**B**	**β**	**t**	**p**
(Intercept)	-4.010		-17.000	< .001
Responding bias	-0.608	-0.268	-2.100	0.040

Note. B = unstandardised coefficient; β = standardised coefficient

aMMN 2nd peak latency (1000Hz as deviant)

Multiple linear regression using backward data entry shows that age, intelligence, WM capacity, and processing speed (see Table 10) significantly explain 11.7% of variance in aMMN 2nd peak latency F(2,56) = 4.836, p = .012, adjusted R squared = .117. Peak latency could be predicted using a regression equation of peak latency = 146.891 + (-.332 * RDS) + (-.282 * Processing speed); peak latency shortens with better WM capacity, and delays with quicker processing speed. Of note, 5.17% of residuals absolute value exceeded two, hence, the regression line might not describe the data the best.

Table 10. Multiple regression for predicting aMMN 2nd peak latency (ms)

Components	**B**	**β**	**t**	**p**
(Intercept)	146.891		47.265	< .001
RDS	-10.139	-0.332	-2.623	0.011
Processing speed	-9.832	-0.282	-2.222	0.030

Note. B = unstandardised coefficent; β = standardised coefficent; RDS = real digit span

vMMN 1st peak latency (B as deviant)

Multiple linear regression using backward data entry shows that responding bias (see Table 11) significantly explain 11% of the variance in vMMN 1st peak latency variable F(1,58) = 7.181, p = .010, R squared = .110. Peak latency could be predicted using a regression equation of peak latency = 200.283 + (-.332* Responding bias); more conservative responding bias shortens peak latency. The Residuals and predicted scatterplot put under question the homoscedasticity of the line.

Table 11. Multiple regression for predicting vMMN 1st peak latency (ms)

Components	**B**	**β**	**t**	**p**
(Intercept)	200.283		37.720	< .001
Responding bias	-17.575	-0.332	-2.680	0.010

Note. B = unstandardised coefficient; β = standardised coefficient

vMMN 2nd peak latency (T as deviant)

Multiple linear regression using backward data entry shows that intelligence, impulsivity, and processing speed (see Table 12) significantly explain 8.9% in the vMMN 2nd peak latency variable F(3,56) = 2.932, p = .041, adjusted R squared = .089. Peak latency could be predicted using a regression equation of peak latency = 209.064 + (.185 * Intelligence) + (.388 * Impulsivity) + (.212* Processing speed); lower impulsivity, lower intelligence, and faster processing speed are related to shorter peak latency. The Residuals and predicted scatter plot suggested a slight violation of homoscedasticity. Of note, 5.08% of residuals absolute value exceeded two, hence, the regression line might not describe the data the best.

Table 12. Multiple regression for predicting Visual 2nd deviant peak latency (ms)

Components	**B**	**β**	**t**	**p**
(Intercept)	204.472		46.680	< .001
Intelligence	7.213	0.185	1.333	0.188
Impulsivity	16.141	0.388	2.873	0.006
Processing speed	8.615	0.212	1.557	0.125

Note. B = unstandardised coefficient; β = standardised coefficient

In total five of the eight MMN components could be predicted through behavioural components (see Table 13). Where responding bias was included in three models, intelligence, RDS and processing speed in two, and impulsivity in one.

Table 13. MMN and behavioural measures

	Intelligence	**Processing speed**	**Responding bias**	**Attention orienting**	**Impulsivity**	**RDS**
aMMN 2nd amplitude	+		-	-		-
aMMN 1st amplitude			-			
aMMN 1st latency		-				-
vMMN 1st latency			-			
vMMN 2nd latency	+	+			+	

Note. + = positive relationship; - = negative relationship; empty = no relationship. aMMN 2nd latency, vMMN 2nd amplitude, vMMN 1st not included since no significant models were found.

Discussion

Preattentive processing was captured by eight aMMN and vMMN components, two for each, amplitude and peak latency. In addition, six components described attentive and cognitive processing, these were intelligence, processing speed, responding bias, impulsivity and RDS. The intelligence component was calculated using the performance on the *n*-back tasks for WM capacity, numerosity task for attention span (Oyama et al., 1981), and EM for fluid intelligence (Raven, 2000). It has been previously found that WM capacity and fluid intelligence follow a similar trend which might be mediated by attentional processing (Brumback et al., 2003), hence, these three components could reflect a similar process. Processing speed included RT measures and DSST. Selective attention included LI-NF and FR scores. Impulsivity components included response inhibition, StRT and LI-FL, a measure of cognitive capacity.

It was expected that higher mental abilities are related to higher MMN amplitude (H1), however the opposite was found. It was shown that higher intelligence relates to decreased aMMN amplitude. To explain such a violation of previous findings, focus is directed towards the contents of the intelligence variable. A possible explanation is that accuracy on *n*-back might not reflect a good score for WM. Meule (2017) has argued that RT and accuracy on *n*-back should be interpreted interchangeably, hence, d' alone might not reflect a score for WM. As well, Berti and Schröger (2003) found no relationship between WM load and MMN amplitude, since their WM task was presented at the same time as the MMN oddball was measured. This suggests that *n*-back, since it was presented at the same time in the current study as well, could have merely been a distraction task that does not reflect the relationship between MMN and attentive processes, such as performance on intelligence measures. In addition, it was hypothesised that there is no relationship between peak latency and intelligence. Yet, it was found that shorter aMMN peak latency is related to higher fluid intelligence score. However, this effect disappeared when multiple variables were taken into account to capture Intelligence. Thus, it is possible that the relationship between mental abilities and MMN peak latency is masked by other processes (Javitt, 1995). Conversely, longer vMMN 2nd peak latency is related to better performance on the intelligence variable. Since the trend is quite inconsistent, this implies that MMN peak latency is not related to mental abilities.

It was also expected that faster processing speed is related to higher peak amplitude and earlier peak latency (H2). Multiple linear regression revealed that quicker processing speed is related to earlier vMMN peak latency, as expected according to previous research (Shin et al., 2017). However, a relationship between aMMN peak latency and *n*-back RT indicates that longer RT results in earlier processing of the stimuli, which is opposite of what was expected. Additionally, the processing speed component is related to aMMN peak latency, hence, longer processing speed delays aMMN peak latency. Hur and colleagues (2017) proposed that during *n*-back task efforts are generally focused on performing accurately rather than as quickly as possible. When adopting such an explanation that people indeed rather focus on accuracy on *n*-back tasks, and perhaps DSST and CRT as well, it could explain why such a trend was found. People who show earlier preattentive processing take time in-between responses, resulting in longer RT and slower behavioural processing speed. However, this was not supported by the data within this study, since accuracy on the *n*-back task was not related to peak latency. Alternatively, it is possible that individual differences in peak latency and processing speed are evident later down the chain of processing and this peak latency difference is due to some other underlying measure. Suggesting that preattentive processing guides performance on RT tasks but is processed later and not captured by MMN.

Next, it was expected that better selective attention is related to higher MMN peak amplitude and shorter peak latency (H3). Indeed, the selective attention component could explain in composition with other variables the variance of aMMN amplitude, implying that higher amplitude is related to more REA. This suggests that people with better deviant discrimination are better at guiding attention and suppressing intrusions from the unattended ear when bottom-up selective attention is necessary (Todd et al., 2011; Asbjornsen & Hugdahl, 1995). Similarly to Chen and colleagues (2015) who found that trouble with attention orienting is related to lower a MMN amplitude. However, a significant positive correlation between LI of the NF condition and vMMN amplitude was found. Meaning that people with higher vMMN amplitude tend to respond more according to information coming from the left ear. This implies that aMMN and vMMN are related to different processes.

It was expected that more left lateralisation on the Dichotic listening FL task is related to higher MMN amplitude and shorter peak latency (H4). Yet, no relationship between FL and MMN was found. However, when looking at the impulsivity score it was found that higher impulsivity score is related to later vMMN peak latency, meaning that more impulsive people show later preattentive deviant processing (H5). Brunas-Wagstaff and colleagues (1994) found that different cognitive processes underlie two types, functional and dysfunctional, of impulsivity. Functional impulsivity is related to rapid information processing at the cost of accuracy, whereas, people who display dysfunctional impulsivity have difficulties with inhibition which is why they make a lot of mistakes and are rather slow at processing. This implies that people with high dysfunctional impulsivity score, but not functional, show delayed vMMN peak latency.

In addition to peak latency, an amplitude change was expected. Such a relationship was possibly not found due to limited impulsivity measure – stRT might have not been a good measure of impulsivity since it does not directly measure impulsive behaviour (Havik et al., 2012). In future studies a Time estimation task can be added for a measure of cognitive tempo.

Further, it was expected that better performance on WM capacity is related to MMN amplitude and not peak latency (H6). Indeed, it was found that higher RDS was associated with higher aMMN amplitude. On the other hand, the relationship between MMN peak latency and WM capacity has not been widely reported. Within our study a relationship between aMMN peak latency and better performance on WMF separately and RDS was found, suggesting that higher WM capacity is related to earlier preattentive processing of auditory stimuli.

It was expected that the choice criterion c reflecting responding bias does not play a role different to d’ accuracy on *n*-back. Keeping in mind that c was captured with *n*-back, a high attentional load task, that was presented at the same time as MMN. Yet, a more conservative responding bias is related to higher aMMN amplitude and shorter vMMN peak latency. More conservative responding bias could be explained through better executive functioning. Snodgrass and Corwin (1988) found that people with Huntington’s disease have a more liberal responding bias than age matched healthy groups. People with Huntington's disease struggle with executive functions such as planning or adapting (Walker, 2007). This implies that people with a more conservative responding bias show a higher MMN amplitude due to better executive functioning. In sum, the relationship between aMMN peak latency and responding bias has not been looked at before which makes this finding interesting and should be looked at if this can be replicated.

To end with, the regression lines explained approximately only 10% of variance in MMN amplitude and peak latency across MMN components, which implies a small relationship. However, that is expected since this study was carried out within a healthy population where high variability is not expected. As well, a lot of variance of MMN is explained by physical features of the stimuli (Näätänen, 1992). While it was expected that aMMN and vMMN are related to similar attentive and cognitive processes the data in the current study does not support this claim. In more accordance with the data is the assumption that aMMN and vMMN are related to different cognitive and attentive processes since pre-attentive processing of auditory and visual information happen at different time stamps.

Limitations and further research

The analysis mostly revealed a relationship between aMMN but not vMMN features. This could be due to the parameters as well as difficulties in the vMMN paradigm. Maekawa and colleagues (2012) brought up that vMMN requires more cooperation from the participant which is why smaller amplitudes might have been produced by vMMN. Hence, the relationship between vMMN and behavioural measures was not as prominent as for aMMN. Since the data used in the current thesis was collected there has been a next wave of data collection with a similar experimental setup and set of tests (reported in Dadatskaja, 2023). During the next wave of data collection, the vMMN stimuli were increased by 30%, which resulted in an increased vMMN amplitude and shortened peak latency (Dadatskaja, 2023). This change in MMN features could help specify the relationship between vMMN and behavioural measures. In future studies, similar analysis can be applied on the data gathered in subsequent stages.

As well, the current study was an explorative one and contained a small sample which could have affected the results. To adequately adopt and interpret PCA the sample size needs to be at least 100 (Suhr, 2005).

Conclusions

The relationship between MMN features and behavioural measures is rather inconsistent. Yet, responding bias seems to be the one behavioural parameter that is closely related to MMN, hence should be included in future studies.

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